CHAPTER 1.

Introduction

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Forests and woodlands cover an extremely large area of the United States, 333 million ha or approximately 36 percent of the Nation's land area (Oswalt and others 2019). These forests possess the capacity to provide a broad range of goods and services for current and future generations, to safeguard biological diversity, and to contribute to the resilience of ecosystems, societies, and economies (USDA Forest Service 2011). Their ecological roles include supplying large and consistent quantities of clean water, preventing soil erosion, and providing habitat for a broad diversity of plant and animal species. Their socioeconomic benefits include wood products, nontimber goods, recreational opportunities, and pleasing natural beauty. Both the ecological integrity and the continued capacity of these forests to provide ecological and economic goods and services are of concern, however, in the face of a long list of threats, including insect and disease infestation, drought, fragmentation and forest conversion to other land uses, catastrophic fire, invasive species, and the effects of climate change.

Natural and anthropogenic stresses vary among biophysical regions and local environments; they also change over time and interact with each other. These and other factors make it challenging to establish baselines of forest health and to detect important departures from normal forest ecosystem functioning (Riitters and Tkacz 2004). Monitoring the health of forests is a critically important task, however, reflected within the Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests (Montréal Process Working Group 1995), which the Forest Service, U.S. Department of Agriculture, uses as a forest sustainability assessment framework (USDA Forest Service 2004, 2011). The primary objective of such monitoring is to identify ecological resources whose condition is deteriorating in subtle ways over large regions in response to cumulative stresses, a goal that requires consistent, large-scale, and long-term monitoring of key indicators of forest health status, change, and trends (Riitters and Tkacz 2004). This is best accomplished through the participation of multiple Federal, State, academic, and private partners.

Although the concept of a healthy forest has universal appeal, forest ecologists and managers have struggled with how exactly to define forest health (Teale and Castello 2011), and there is no universally accepted definition. Most definitions of forest health can be categorized as representing either an ecological or a utilitarian perspective (Kolb and others 1994). From an ecological perspective, the current understanding of ecosystem dynamics suggests that healthy ecosystems are those that are able to maintain their organization and autonomy over time while remaining resilient to stress (Costanza 1992), and that evaluations of forest health should emphasize factors that affect the inherent processes and resilience of forests (Edmonds and others 2011, Kolb and others 1994, Raffa and others 2009). On the other hand, the utilitarian

perspective holds that a forest is healthy if management objectives are met, and that a forest is unhealthy if these objectives are not met (Kolb and others 1994). Although this definition may be appropriate when a single, unambiguous management objective exists, such as the production of wood fiber or the maintenance of wilderness attributes, it is too narrow when multiple management objectives are required (Edmonds and others 2011, Teale and Castello 2011). Teale and Castello (2011) incorporate both ecological and utilitarian perspectives into their two-component definition of forest health: first, a healthy forest must be sustainable with respect to its size structure, including a correspondence between baseline and observed mortality; second, a healthy forest must meet the landowner's objectives, provided that these objectives do not conflict with sustainability.

This national report, the 20th in an annual series sponsored by the Forest Health Monitoring (FHM) program of the Forest Service, attempts to quantify the status of, changes to, and trends in a wide variety of broadly defined indicators of forest health. The indicators described in this report encompass forest insect and disease activity, wildland fire occurrence, drought, tree mortality, and coarse woody materials, among others. The previous reports in this series are Ambrose and Conkling (2007, 2009), Conkling (2011), Conkling and others (2005), Coulston and others (2005a, 2005b, 2005c), and Potter and Conkling (2012a, 2012b, 2013a, 2013b, 2014, 2015a, 2015b, 2016, 2017, 2018, 2019,

2020). Visit https://www.fs.fed.us/foresthealth/ publications/fhm/fhm-annual-national-reports. shtml for links to each of these reports in their entirety and for searchable lists of links to chapters included in the reports.

This report has three specific objectives. The first is to present information about forest health from a national perspective, or from a multi-State regional perspective when appropriate, using data collected by the Forest Health Protection (FHP) and Forest Inventory and Analysis (FIA) programs of the Forest Service, as well as from other sources available at a wide extent. The chapters that present analyses at a national scale, or multi-State regional scale, are divided between section 1 and section 2 of the report. Section 1 presents results from the analyses of forest health data that are available on an annual basis. Such repeated analyses of regularly collected indicator measurements allow for the detection of trends over time and help establish a baseline for future comparisons (Riitters and Tkacz 2004). Section 2 presents longer-term forest health trends, in addition to describing new techniques for analyzing forest health data at national or regional scales (the second objective of the report). While in-depth interpretation and analysis of specific geographic or ecological regions are beyond the scope of these parts of the report, the chapters in sections 1 and 2 present information that can be used to identify areas that may require investigation at a finer scale.
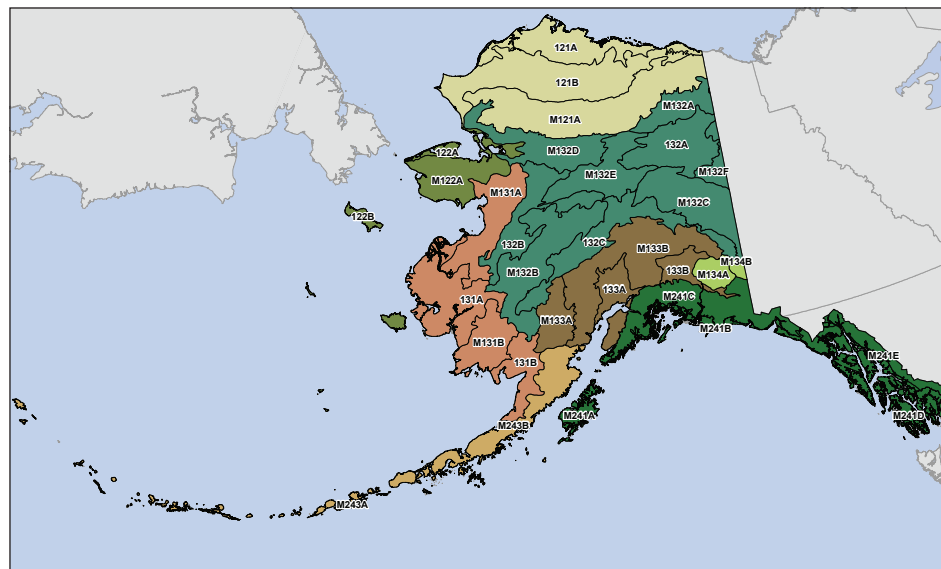
The second objective of the report is to present new techniques for analyzing forest health data as well as new applications of established techniques, often applied to longer timescales, presented in selected chapters of section 2. Examples in this report are chapters 6 and 7. Chapter 6 presents the results of analyses of nearly 20 years of FIA coarse woody material (CWM) data across spatial scales to assess change over time in CWM biomass, diameter and decay class, and species composition. Chapter 7, meanwhile, uses case studies to demonstrate the potential of rFIA, an open-source R package developed to improve the accessibility of FIA data and offer enhanced flexibility in estimation strategies, to advance forest health evaluation and monitoring.

The third objective of the report is to present results of recently completed Evaluation Monitoring (EM) projects funded through the FHM national program. These project summaries, presented in section 3, determine the extent, severity, and/or cause of forest health problems (FHM 2019), generally at a finer scale than that addressed by the analyses in sections 1 and 2. Each of the six chapters in section 3 contains an overview of an EM project, key results, and contacts for more information.

When appropriate throughout this report, authors use the Forest Service revised ecoregions for the conterminous United States and Alaska (Cleland and others 2007, Spencer and others 2002) as a common ecologically based spatial framework for their forest health assessments (fig. 1.1). Specifically, when the spatial scale of the data and the expectation of an identifiable pattern in the data are appropriate, authors use ecoregion sections, larger-scale provinces, or smaller-scale subsections as assessment units for their analyses. Bailey's hierarchical system bases the two broadest ecoregion scales, domains and divisions, on large ecological climate zones, while each division is broken into provinces based on vegetation macro features (Bailey 1995). Provinces are further divided into sections, which may be thousands of km^2 in area and are expected to encompass regions similar in their geology, climate, soils, potential natural vegetation, and potential natural communities (Cleland and others 1997). Subsections are nested within sections as the smallest level in the hierarchy. This hierarchical system does not address either Hawaii or Puerto Rico beyond including each in a unique, single ecoregion province (Bailey 1995). A set of Hawaii ecoregions based on moisture and elevational characteristics was developed for use in FHM national reports (Potter 2020) because a finer-scale and ecologically oriented spatial assessment framework was needed to estimate the impacts of a destructive forest disease (ch. 2) and of forest fire occurrences (ch. 3) (fig. 1.2, table 1.1).

Figure 1.1—Ecoregion provinces and sections for (A) the conterminous United States (Cleland and others 2007) and (B) Alaska (Spencer and others 2002). Ecoregion sections within each ecoregion province are shown in the same color.

Conterminous States ecoregion provinces

- 211: Northeastern Mixed Forest
- M211: Adirondack-New England Mixed Forest—Coniferous Forest—Alpine Meadow
- 212: Laurentian Mixed Forest
- 221: Eastern Broadleaf Forest
- M221: Central Appalachian Broadleaf Forest—Coniferous Forest—Meadow
- 222: Midwest Broadleaf Forest
- 223: Central Interior Broadleaf Forest
- M223: Ozark Broadleaf Forest
- 231: Southeastern Mixed Forest
- M231: Ouachita Mixed Forest—Meadow
- 232: Outer Coastal Plain Mixed Forest
- 234: Lower Mississippi Riverine Forest
- 242: Pacific Lowland Mixed Forest
- 251: Prairie Parkland (Temperate)
- 255: Prairie Parkland (Subtropical)
- M242: Cascade Mixed Forest—Coniferous Forest—Alpine Meadow
- 261: California Coastal Chaparral Forest and Shrub
- M261: Sierran Steppe—Mixed Forest—Coniferous Forest—Alpine Meadow
- 262: California Dry Steppe
- M262: California Coastal Range Open Woodland—Shrub—Coniferous Forest—Meadow
- 263: California Coastal Steppe—Mixed Forest—Redwood Forest
- 313: Colorado Plateau Semi-Desert
- M313: Arizona-New Mexico Mountains Semi-Desert—Open Woodland—Coniferous Forest—Alpine Meadow
- 315: Southwest Plateau and Plains Dry Steppe and Shrub
- 321: Chihuahuan Semi-Desert
- 322: American Semi-Desert and Desert
- 331: Great Plains—Palouse Dry Steppe
- M331: Southern Rocky Mountain Steppe—Open Woodland—Coniferous Forest—Alpine Meadow
- 332: Great Plains Steppe
- M332: Middle Rocky Mountain Steppe—Coniferous Forest—Alpine Meadow
- M333: Northern Rocky Mountain Forest-Steppe—Coniferous Forest—Alpine Meadow
- M334: Black Hills Coniferous Forest
- 341: Intermountain Semi-Desert and Desert
- M341: Nevada-Utah Mountains Semi-Desert—Coniferous Forest—Alpine Meadow
- 342: Intermountain Semi-Desert
- 411: Everglades

Alaska ecoregion provinces

- 121: Arctic Tundra
- M122: Bering Tundra
- M131: Bering Taiga
- M132: Intermontane Boreal
- 133: Alaska Range Transition
- M134: Coastal Mountains Transition
- M241: Coastal Rainforest
- M243: Aleutian Meadows
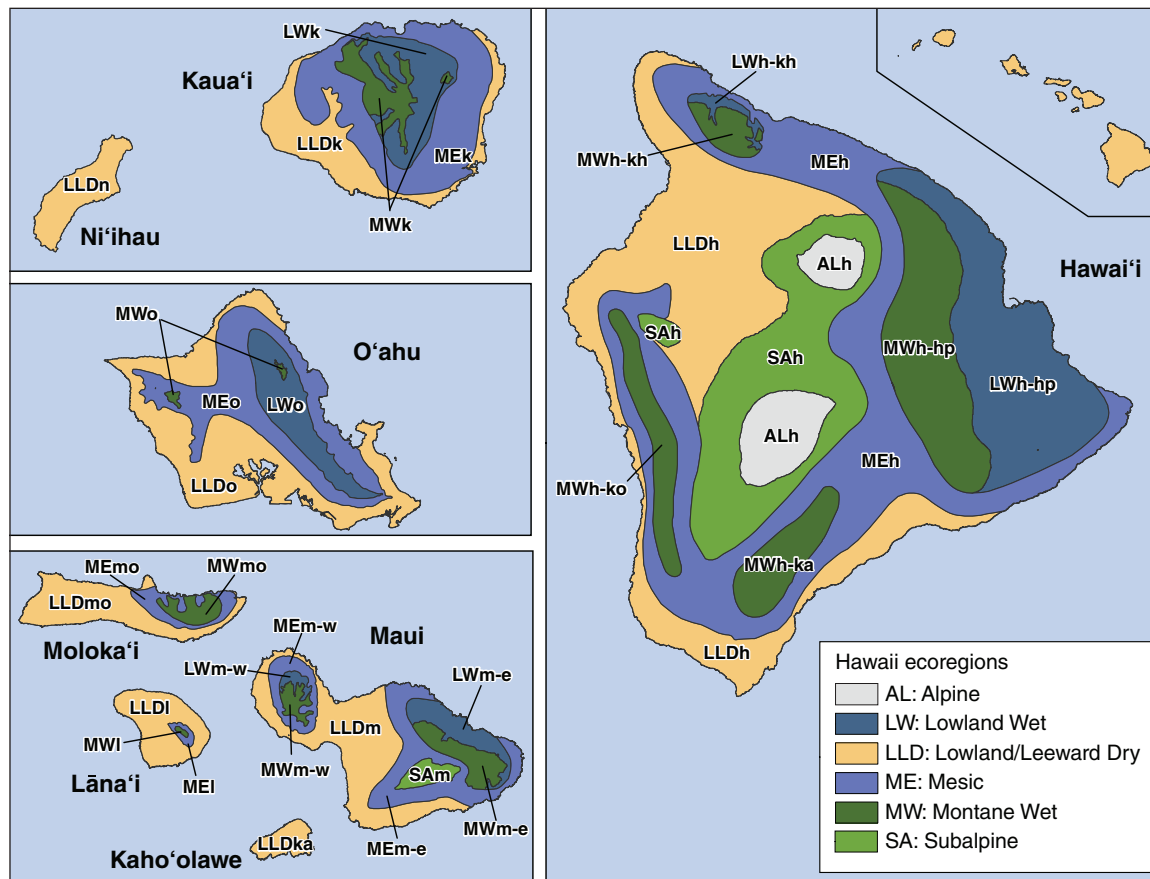
Figure 1.2—Ecoregions, and ecoregion subunits, for Hawaii, developed based on moisture zones and elevation (see box 1.1). Ecoregion subunits are shown in the same color by ecoregion. See table 1.1 for the names of the ecoregion subunits listed on the map.

Table 1.1—The six ecoregions and 34 ecoregion subunits for the State of Hawaii

Ecoregion	Subunit		Ecoregion	Subunit
AL: Alpine	Alh: Alpine-Hawai'i		MW: Montane Wet	MWh-hp: Montane Wet-Hawai'i-Hilo-Puna
				MWh-ka: Montane Wet-Hawai'i-Ka'ū
LW: Lowland Wet	LWh-hp: Lowland Wet-Hawai'i-Hilo-Puna			MWh-kh: Montane Wet-Hawai'i-Kohala-Hāmākua
	LWh-kh: Lowland Wet-Hawai'i-Kohala-Hāmākua			MWh-ko: Montane Wet-Hawai'i-Kona
	LWk: Lowland Wet-Kaua'i			MWk: Montane Wet-Kaua'i
	LWm-e: Lowland Wet-Maui-East			MWl: Montane Wet-Lāna'i
	LWm-w: Lowland Wet-Maui-West			MWm-e: Montane Wet-Maui-East
	LWo: Lowland Wet-O'ahu			MWm-w: Montane Wet-Maui-West
				MWmo: Montane Wet-Moloka'i
LLD: Lowland/Leeward Dry	LLDh: Lowland/Leeward Dry-Hawai'i			MWo: Montane Wet-O'ahu
	LLDka: Lowland/Leeward Dry-Kaho'olawe			
	LLDk: Lowland/Leeward Dry-Kaua'i		SA: Subalpine	SAh: Subalpine-Hawai'i
	LLDl: Lowland/Leeward Dry-Lāna'i			SAm: Subalpine-Maui
	LLDm: Lowland/Leeward Dry-Maui			
	LLDmo: Lowland/Leeward Dry-Moloka'i			
	LLDn: Lowland/Leeward Dry-Ni'ihau			
	LLDo: Lowland/Leeward Dry-O'ahu			
ME: Mesic	MEh: Mesic-Hawai'i			
	MEk: Mesic-Kaua'i			
	MEl: Mesic-Lāna'i			
	MEm-e: Mesic-Maui-East			
	MEm-w: Mesic-Maui-West			
	MEmo: Mesic-Moloka'i			
	MEo: Mesic-O'ahu			

THE FOREST HEALTH MONITORING PROGRAM

The national FHM program is designed to determine the status, changes, and trends in indicators of forest condition on an annual basis and covers all forested lands through a partnership encompassing the Forest Service, State foresters, and other State and Federal agencies and academic groups (FHM 2019). The FHM program utilizes data from a wide variety of data sources, both inside and outside the Forest Service, and develops analytical approaches for addressing forest health issues that affect the sustainability of forest ecosystems. The FHM program has four major components (fig. 1.3):

- Detection Monitoring—nationally standardized aerial and ground surveys to evaluate status and change in condition of forest ecosystems (sections 1 and 2 of this report)

- Evaluation Monitoring—projects to determine the extent, severity, and causes of undesirable changes in forest health identified through Detection Monitoring (section 3 of this report)

- Research on Monitoring Techniques—work to develop or improve indicators, monitoring systems, and analytical techniques, such as urban and riparian forest health monitoring, early detection of invasive species, multivariate analyses of forest health indicators, and spatial scan statistics (section 2 of this report)
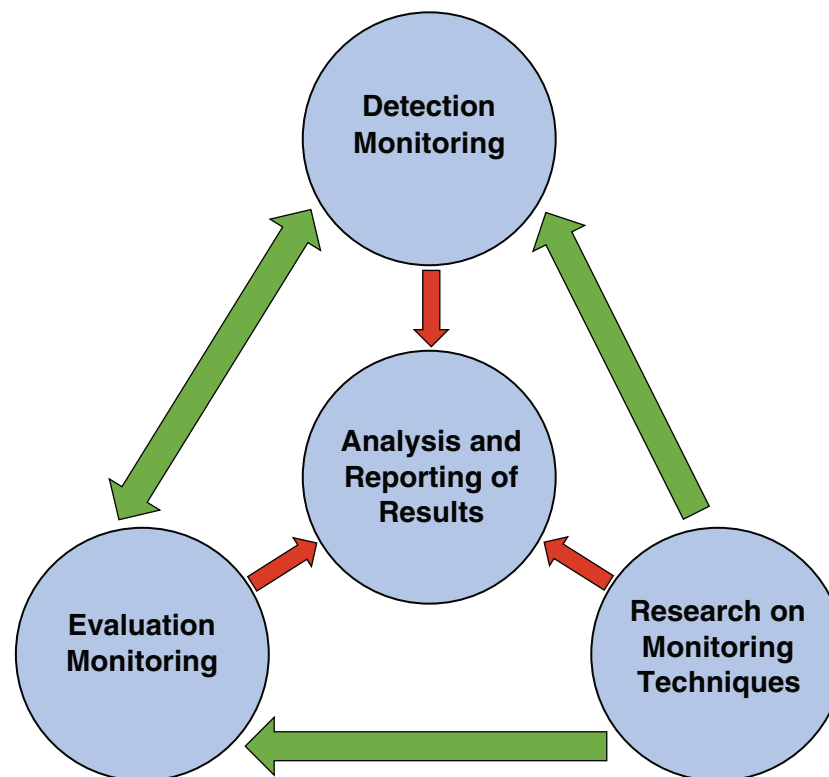
Figure 1.3—*The design of the Forest Health Monitoring program (FHM 2003).*

- Analysis and Reporting—synthesis of information from various data sources within and external to the Forest Service to produce issue-driven reports on status and change in forest health at national, regional, and State levels (sections 1, 2, and 3 of this report)

The FHM program, in addition to national reporting, generates regional and State reports, often in cooperation with FHM partners, both within the Forest Service and in State forestry and agricultural departments. For example, the FHM regions cooperate with their respective State partners to produce the annual Forest Health Highlights report series, available on the FHM website at https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml. Other examples include Steinman (2004) and Harris and others (2011).

The FHM program and its partners also produce reports and journal articles on monitoring techniques and analytical methods (see https://www.fs.fed.us/foresthealth/publications/fhm/fhm-publications.shtml). The emphases of these publications include forest health data (Potter and others 2016, Siry and others 2018, Smith and Conkling 2004); soils as an indicator of forest health (O'Neill and others 2005); urban forest health monitoring (Bigsby and others 2014; Cumming and others 2006, 2007; Lake and others 2006); remote sensing of forest disturbances (Chastain and others 2015, Rebbeck and others 2015); health conditions in national forests (Morin and others 2006); crown conditions (Morin and others 2015; Randolph 2010a, 2010b, 2013; Randolph and Moser 2009; Schomaker and others 2007); indicators of regeneration (McWilliams and others 2015); vegetation diversity and structure (Schulz and Gray 2013, Schulz and others 2009, Simkin and others 2016); forest lichen communities (Jovan and others 2012, Root and others 2014); down woody materials in forests (Woodall and others 2012, 2013); drought (Vose and others 2016); ozone monitoring (Rose and Coulston 2009); patterns of nonnative invasive plant occurrence (Guo and others 2015, 2017; Iannone and others 2015, 2016a, 2016b, 2018; Jo and others 2018; Oswalt and others 2015; Riitters and others 2018a, 2018b); assessments of forest risk or tree species vulnerability to exotic invasive forest insects and diseases (Koch and others 2011, 2014; Krist and others 2014; Potter and others 2019a, 2019b; Vogt and Koch 2016; Yemshanov and others 2014); spatial patterns of landcover and forest fragmentation (Guo and others 2018; Riitters 2011; Riitters and Costanza 2019; Riitters and Wickham 2012; Riitters and others 2012, 2016, 2017); impacts of deer browse on forest structure (Russell and others 2017); broad-scale assessments of forest biodiversity (Guo and others 2019; Potter 2018; Potter and Koch 2014; Potter and Woodall 2012, 2014); predictions and indicators of climate change effects on forests and forest tree species (Fei and others 2017, Heath and others 2015, Potter and Hargrove 2013); and the overall forest health indicator program (Woodall and others 2010).

For more information about the FHM program, visit the FHM website at https://www.fs.fed.us/foresthealth/protecting-forest/forest-health-monitoring/. Among other resources,

this website includes links to all past national forest health reports (https://www.fs.fed.us/ foresthealth/publications/fhm/fhm-annual-national-reports.shtml), and annual State Forest Health Highlights reports (https://www.fs.fed. us/foresthealth/protecting-forest/forest-health-monitoring/monitoring-forest-highlights.shtml).

DATA SOURCES

Forest Service data sources in this edition of the FHM national report include FIA annualized Phase 2 survey data (Bechtold and Patterson 2005, Burrill and others 2018, Woodall and others 2010); FHP national Insect and Disease Survey forest mortality and defoliation data for 2019 (FHP 2020); Moderate Resolution Imaging Spectroradiometer (MODIS) Active Fire Detections for the United States data for 2019 (USDA Forest Service 2020); tree canopy cover data generated from the 2011 National Land Cover Database (NLCD) (Homer and others 2015) through a cooperative project between the Multi-Resolution Land Characteristics Consortium and Forest Service Geospatial Technology and Applications Center (GTAC) (Coulston and others 2012); and FIA's publicly available Environmental Monitoring and

Assessment Program (EMAP) hexagons (Brand and others 2000). Other sources of data include Parameter-elevation Regression on Independent Slopes Model (PRISM) climate mapping system data (PRISM Climate Group 2020), and Alaskan forest and shrub cover derived from the 2011 NLCD. For more information about the FIA program, which is a major source of data for several FHM analyses, see box 1.1.

FHM REPORT PRODUCTION

This FHM national report, the 20th in a series of such annual documents, is produced by forest health monitoring researchers at the Eastern Forest Environmental Threat Assessment Center (EFETAC) in collaboration with North Carolina State University cooperators in the Forest Health Monitoring Research Group (https://go.ncsu.edu/foresthealth). A unit of the Southern Research Station of the Forest Service, EFETAC was established under the Healthy Forests Restoration Act of 2003 to generate the knowledge and tools needed to anticipate and respond to environmental threats. For more information about the research team and about threats to U.S. forests, please visit https://www. forestthreats.org/about.
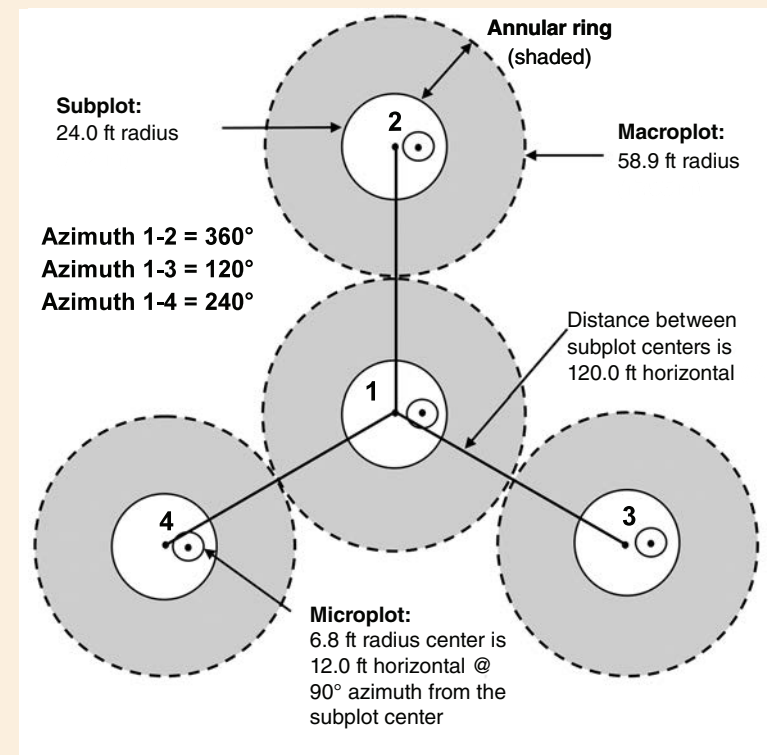
Box 1.1

The Forest Inventory and Analysis (FIA) program collects forest inventory information across all forest land ownerships in the United States and maintains a network of more than 130,000 permanent forested ground plots across the conterminous United States, southeastern Alaska, Hawaii, and the Caribbean and Pacific territories with a sampling intensity of approximately one plot/2428 ha (one plot per 6,000 acres). Forest Inventory and Analysis Phase 2 encompasses the annualized inventory measured on plots at regular intervals, with each plot surveyed every 5 to 7 years in most Eastern States, but with plots in the Rocky Mountain and Pacific Northwest regions surveyed once every 10 years (Reams and others 2005). The standard 0.067-ha plot (see figure) consists of four 7.315-m (24-foot) radius subplots (approximately 168.6 m^2 or 1/24th acre), on which field crews measure trees at least 12.7 cm (5 inches) in diameter. Within each of these subplots is nested a 2.073-m (6.8-foot) radius microplot (approximately 13.48 m^2 or 1/300th acre), on which crews measure trees smaller than 12.7 cm (5 inches) in diameter. A core-optional variant of the standard design includes four "macroplots," each with a radius of 17.953 m or 58.9 feet (approximately 0.1012 ha or 1/4 acre) that originates at the center of each subplot (Burrill and others 2018).

Forest Inventory and Analysis Phase 3 plots previously represented a subset of these Phase 2 plots, with one Phase 3 plot for every 16 standard FIA Phase 2 plots. In addition to traditional forest inventory measurements, data for a variety of important ecological indicators were from Phase 3 plots, including tree crown condition, lichen communities, down woody material, soil condition, and vegetation structure and diversity, whereas data on ozone bioindicator plants were collected on a separate grid of plots (Woodall and others 2010, 2011). Most of these additional forest health indicators were measured as part of the Forest Health Monitoring Detection Monitoring ground plot system prior to 2000[1] (Palmer and others 1991). The FIA program recently updated its sampling techniques with flexible spatial and temporal intensities for some of these ecosystem health indicators (including down woody material, vegetation diversity and structure, and crown conditions) to improve field operation efficiency, address emerging user demands, and adjust to evolving forest health science (Castillo and Alvarez 2020). This "Phase 2 Plus Program/ Ecosystem Indicator Program" (P2+) sampling scheme facilitates the collection of a national core set of indicator information on more plots for less cost than the original indicator protocols, with sampling based on a systematic subsample that can change in response to budgetary fluctuations without compromising long-term analytical capabilities. The enhanced indicator protocols collect less-detailed information on each sampled plot than on the previous Phase 3 plots, but substantially more plots are sampled, increasing the statistical power of forest health analyses and improving the reliability of estimates in important national assessments (Castillo and Alvarez 2020).

[1] U.S. Department of Agriculture Forest Service. 1998. Forest Health Monitoring 1998 field methods guide. Research Triangle Park, NC: U.S. Department of Agriculture Forest Service, Forest Health Monitoring program. 473 p. On file with: Forest Health Monitoring program, 3041 Cornwallis Rd., Research Triangle Park, NC 27709.

Box 1.1 figure—The Forest Inventory and Analysis mapped plot design. Subplot 1 is the center of the cluster with subplots 2, 3, and 4 located 120 feet away at azimuths of 360°, 120°, and 240°, respectively (Burrill and others 2018).

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